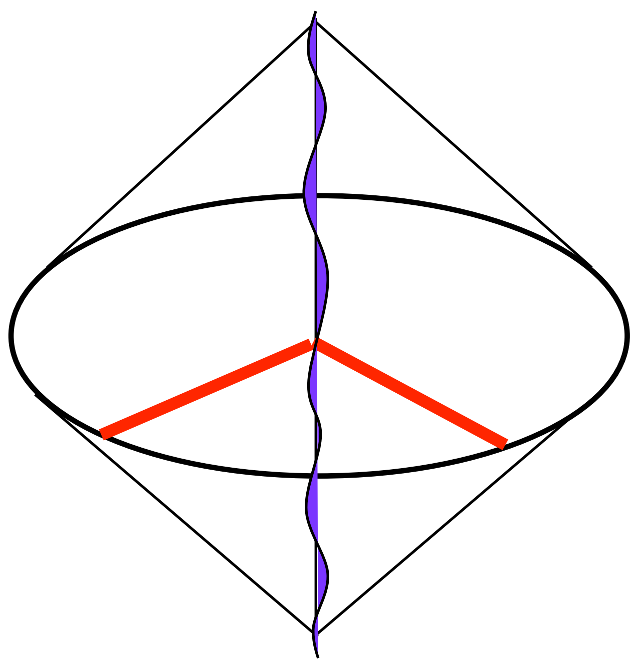
Holographic Noise in Interferometers

A new experimental probe of Planck scale unification



Craig Hogan

University of Chicago and Fermilab

Interferometers might probe Planck scale physics

One interpretation of the Planck frequency limit predicts a new kind of uncertainty leading to a new detectable effect:

"holographic noise"

Different from gravitational waves or quantum field fluctuations

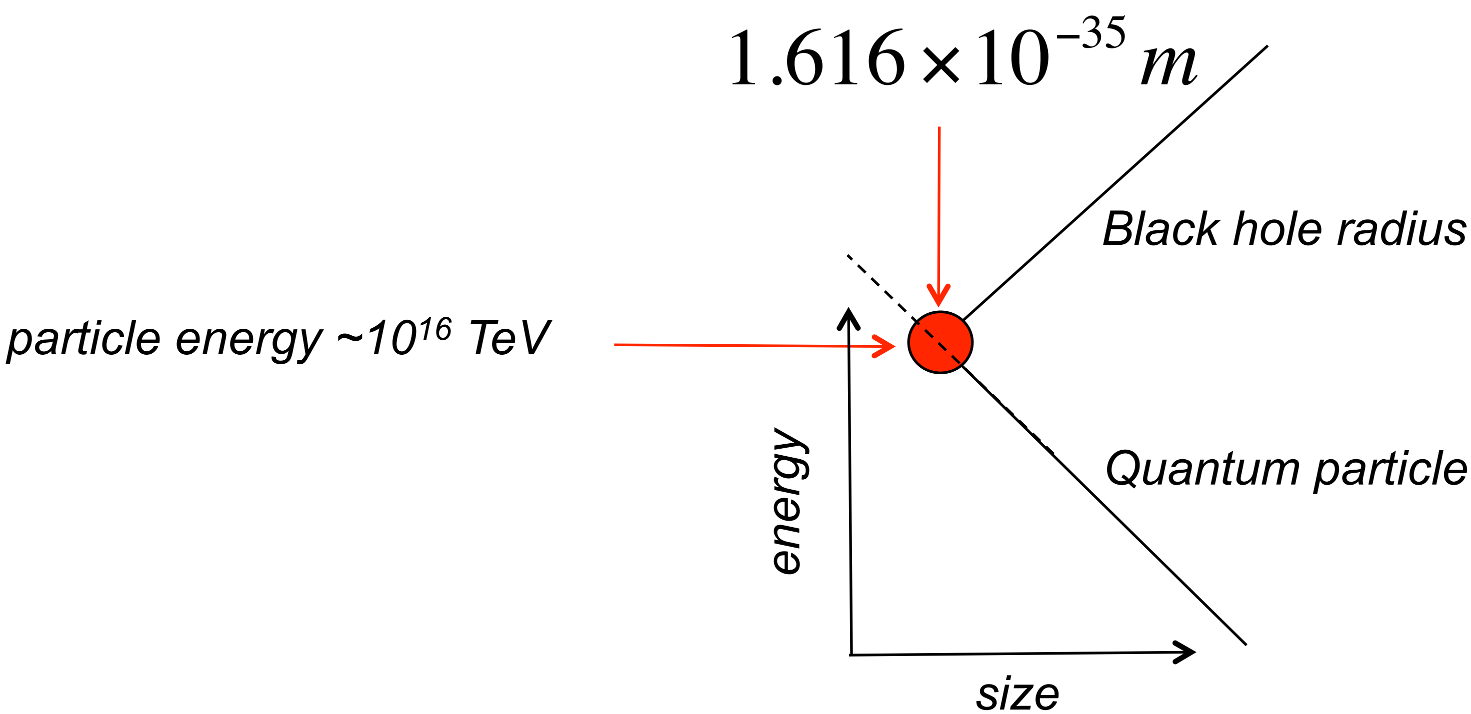
Predicts Planck-amplitude noise spectrum with no parameters

We are designing an experiment to test this hypothesis

Planck scale

$$t_P \equiv l_P/c \equiv \sqrt{\hbar G_N/c^5} = 5 \times 10^{-44} \text{ seconds}$$

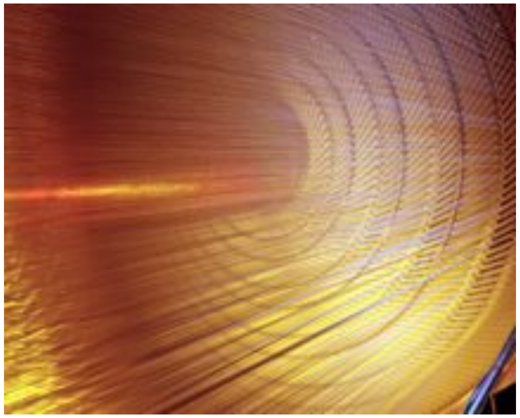
The physics of this "minimum time" is unknown



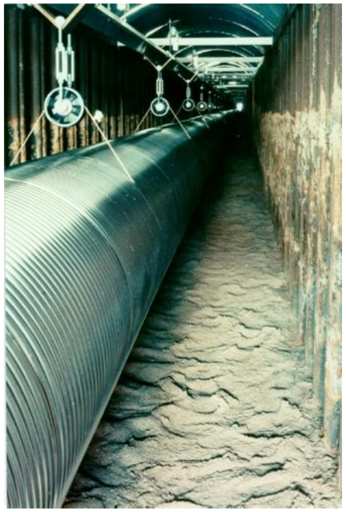
Particle confined to Planck volume makes its own black hole

Two ways to study small scales

CERN and Fermilab particle colliders rip particles into tiny pieces —tiny, but not small enough



Interferometers may sense nonlocal jitter from the wave character of spacetime

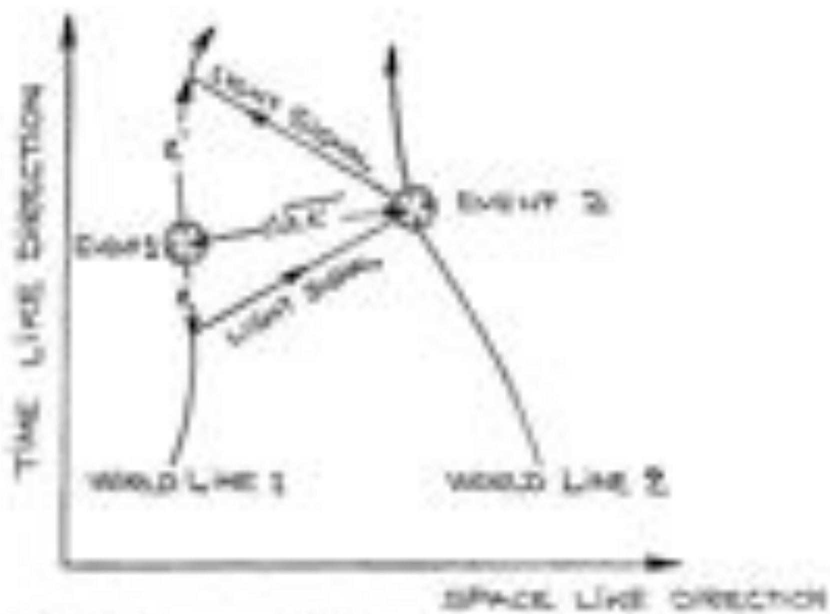


Quantum limits on measuring event positions

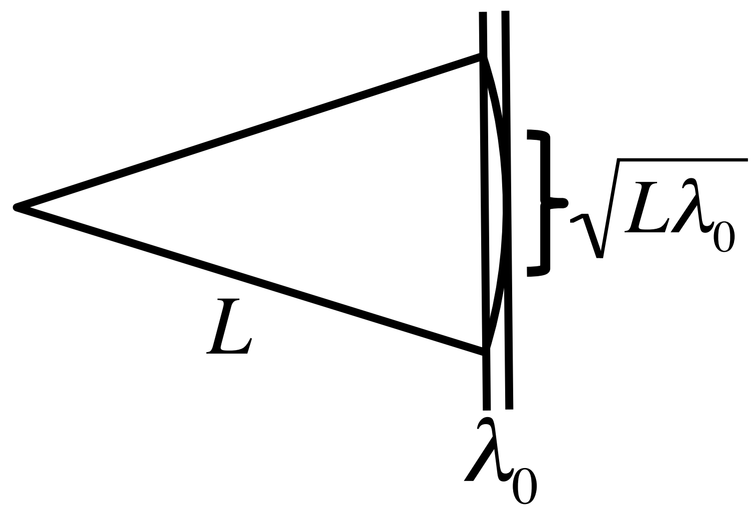
Spacelike-separated event intervals can be defined with clocks and light

But transverse position measured with frequency-bounded waves is uncertain by the diffraction limit, $\sqrt{L\lambda_0}$

This is much larger than the wavelength

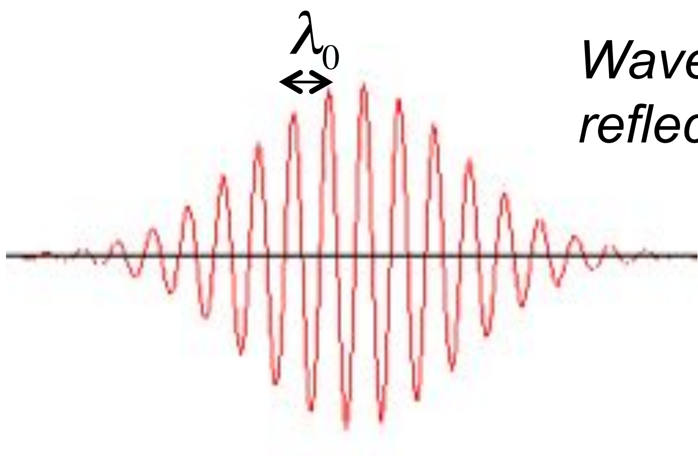


Wigner (1957): quantum limits with one spacelike dimension



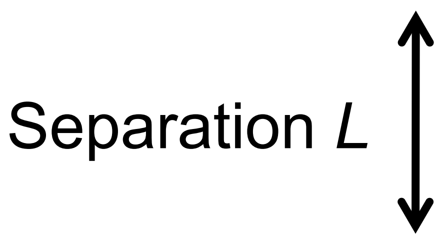
Add second dimension: small phase difference of events over large transverse patch

Nonlocal comparison of event positions: phases of frequency-bounded wavepackets



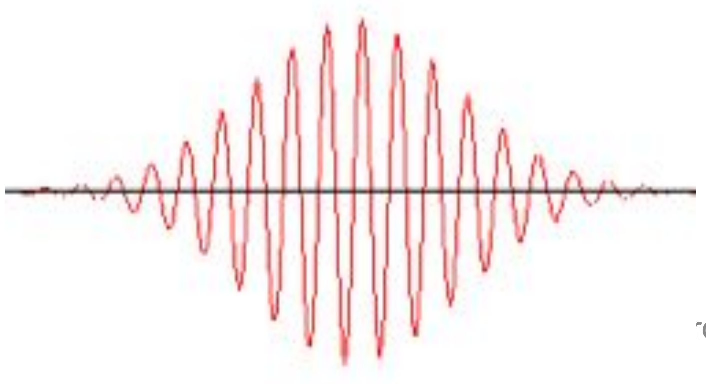
Wavefunction of relative positions of null-field reflections off massive bodies

$$\Delta f = c / 2\pi\Delta x$$



$$\Delta\phi = (2\pi L / \lambda_0)(\Delta f / f_0)$$

$$\Delta x_L = \Delta\phi(\lambda_0 / 2\pi) = L(\Delta f / f_0) = \sqrt{\lambda_0 L / 2\pi}$$



Uncertainty depends only on L, λ_0

Quantum limit of an interferometer of size *L*

Heisenberg uncertainties of mirror position along arm 1 and photon momentum along arm 2

$$\Delta x_1 > \hbar / 2\Delta p_2$$

Uncertainty of transverse position from measured phase

$$\Delta x_2 > L(\Delta p_2 / p_0)$$

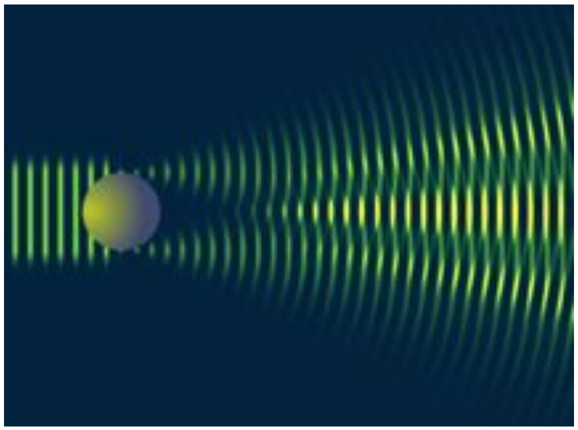
Uncertainty in difference

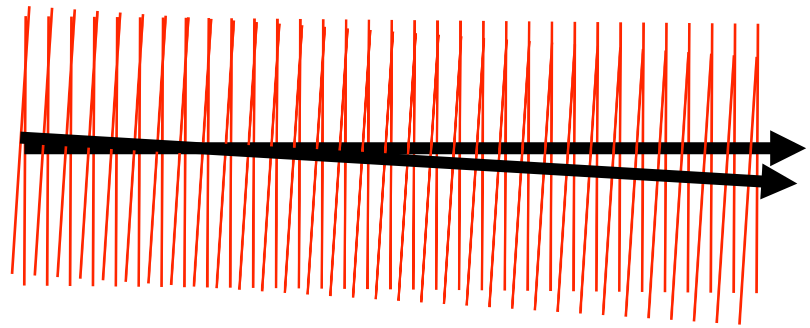
$$\Delta x_{1-2}^2 > \lambda_0 L / 2\pi$$

~ diffraction limit: does not depend on masses

No "better measurement" of transverse position is possible with single wave quanta

A new uncertainty of spacetime?





Suppose the Planck scale is a minimum wavelength

Then transverse event positions may be fundamentally uncertain by the Planck diffraction limit

Classical direction ~ ray approximation of a Planck wave

Visualizing the effect: Diffractive blurring in holograms

If you "lived inside" a hologram, you could tell by measuring the blurring

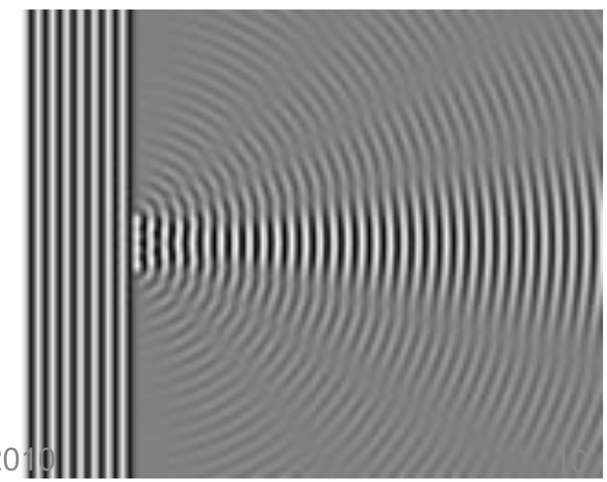
Blurring much bigger than wavelength:

$$D = \sqrt{\lambda L}$$

is the transverse resolution at a distance *L*

(*D* ~ 1mm for an optical hologram at L~ 1m)

examples from wave optics

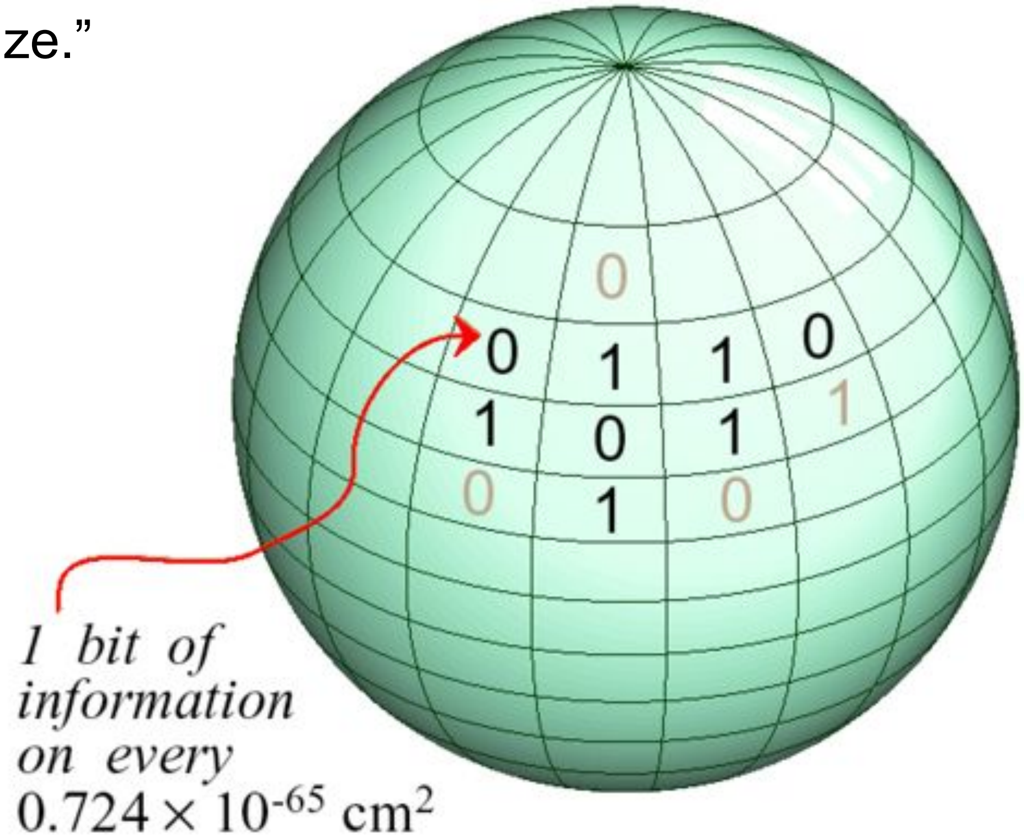


Wave patterns much larger than the wavelength

Bold idea from black hole physics: the world is a hologram

“This is what we found out about Nature’s book keeping system: the data can be written onto a surface, and the pen with which the data are written has a finite size.”

-Gerard ‘t Hooft



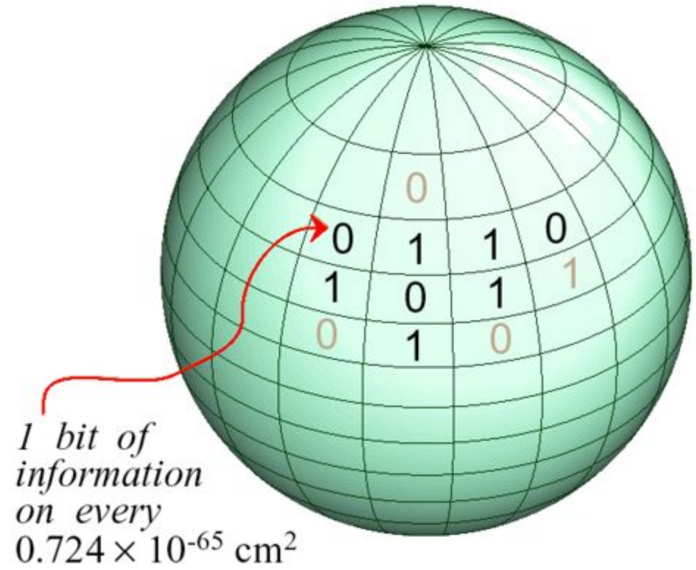
Holographic Principle

Black hole thermodynamics and evaporation

Universal covariant entropy bound

AdS/CFT type dualities in string theory

Matrix theory



All suggest theory on 2+1 D null surfaces with Planck scale bound

But there is no agreement on what it means for experiments

Bekenstein, Hawking, Bardeen et al., 'tHooft, Susskind, Bousso, Srednicki, Jacobson, Banks, Fischler, Shenker, Unruh

Possible consequence of holography

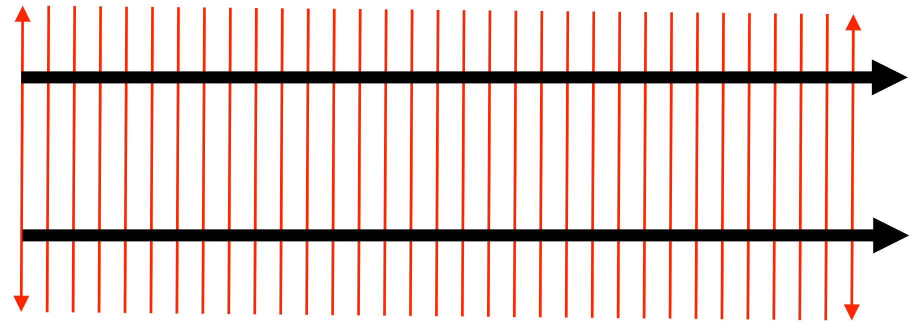
Hypothesis: observable correlations are encoded on light sheets and limited by information capacity of a Planck wavelength carrier ("Planck information flux" limit)

Predicts uncertainty in position at Planck diffraction scale

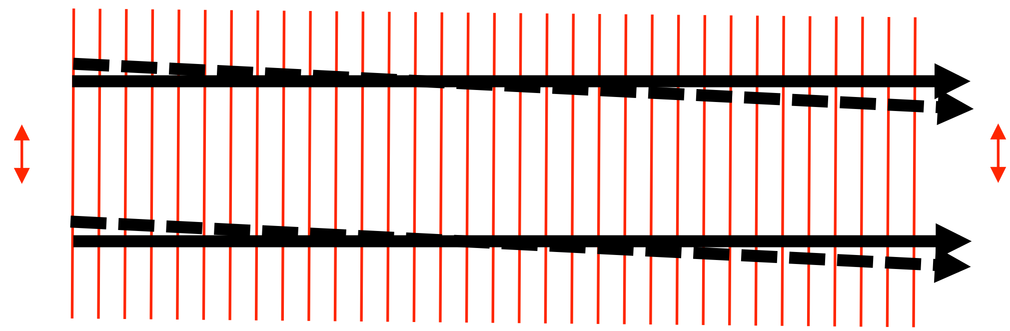
Allows calculation of experimental consequences

- Matter jitters about geodesics defined by massless fields
- ~ Planck length per Planck time
- Only in the transverse (in-wavefront) directions
- Quantum effect: state depends on measurement
- Coherent phase gives coherent transverse jitter on scale L

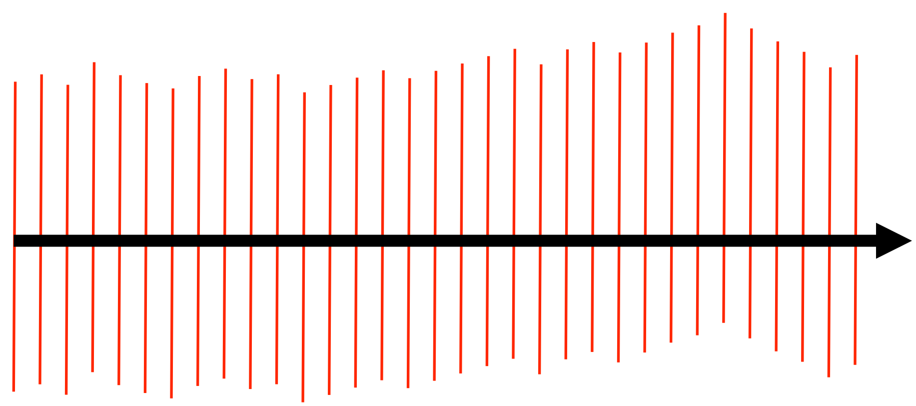
Rays in direction normal
to Planck wavefronts



Localize in wavefront:
transverse momentum,
angular uncertainty



wavefunction of position:
transverse uncertainty,
Planck diffraction/jitter,
transverse coherence



A candidate phenomenon of unified theory

Fundamental theory (Matrix, string, loop,…)

↕

Effective theory (Planck frequency limit, carrier wave, diffractive transverse position uncertainty)

↕

Observables in classical apparatus (effective beamsplitter motion, holographic noise in interferometer signals)

Black Hole Thermodynamics

Bekenstein, Bardeen et al. (~1972): laws of black hole thermodynamics

Area of (null) event horizon, like entropy, always increases

Entropy ~ event horizon area in Planck units (not volume)

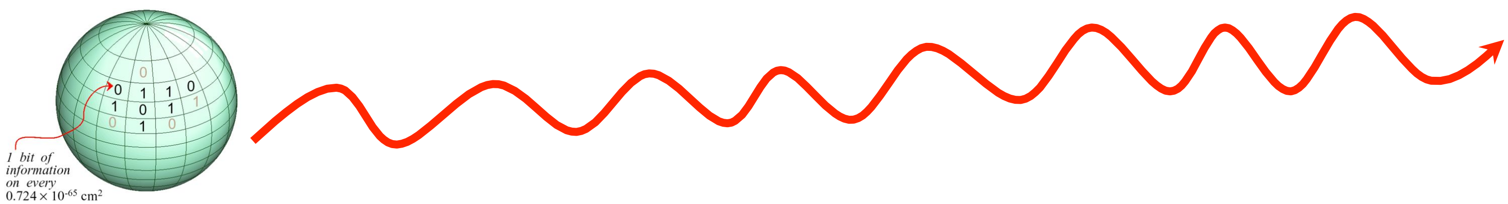
Is there is a deep reason connected with microscopic degrees of freedom encoded on any 2D null surface?

Black Hole Evaporation: a clue to unification

Hawking (1975): black holes slowly radiate particles, lose energy

convert "pure spacetime" into normal particles like light

number of particles ~ area of the surface in Planck units



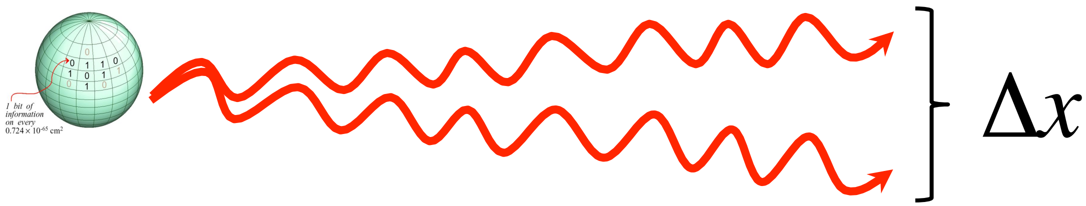
Unitary black hole evaporation

Initial state: black hole (spacetime vacuum)

Final state: particles in flat spacetime

Numbers of initial and final states must match

Record images of final particles, count their states



- one particle evaporates per Planck area
- position recorded on film at distance *L* (violates *s* wave symmetry)
- wavelength ~ hole size *R*

standard position uncertainty $\Delta x > R$

Particle images on distant film must have fewer "pixels" than black hole

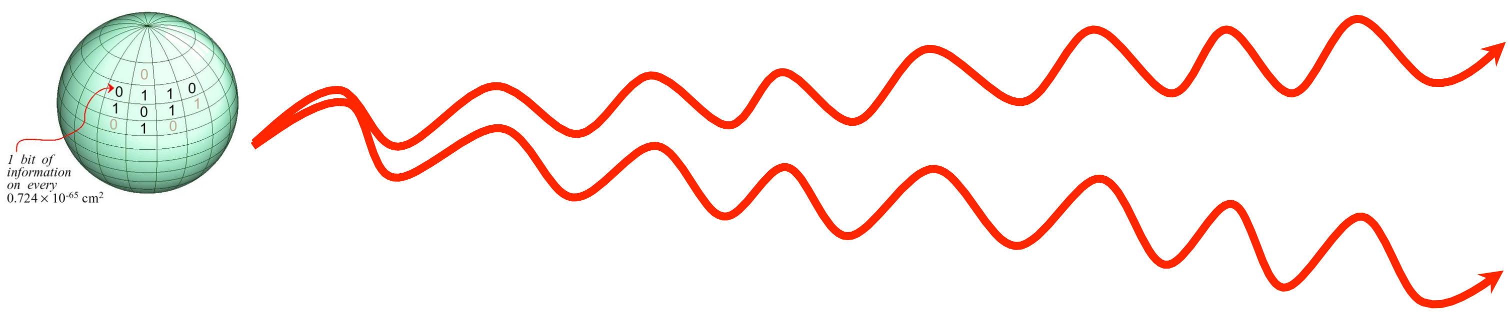
$$(L/\Delta x)^2 < (R/\lambda_P)^2$$

Requires transverse uncertainty in arrival position at large distance *L*

$$\Delta x > \sqrt{\lambda_P L}$$

Uncertainty independent of black hole R

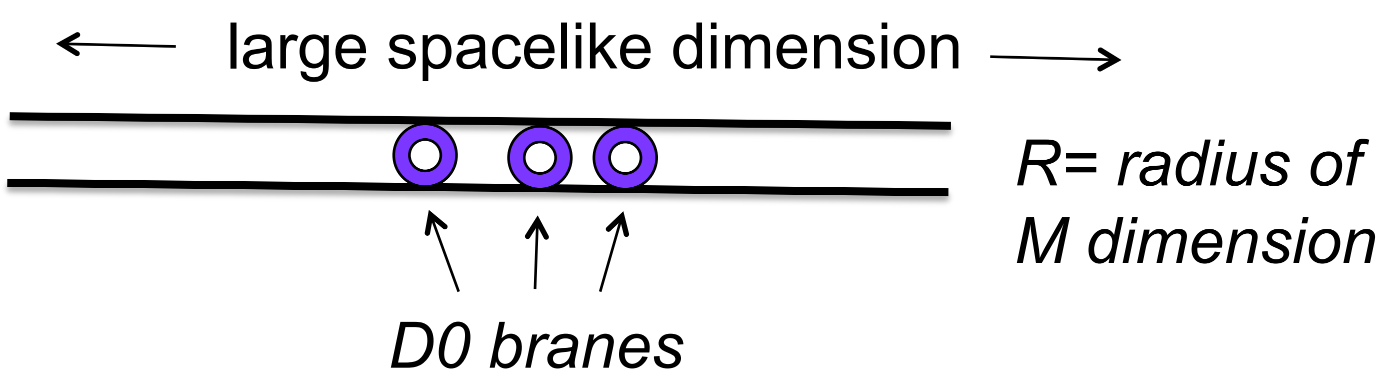
New “holographic” uncertainty of distant position….with or without a black hole



Black hole calibrates the effect: no parameters

Example of holographic unification: one interpretation of Matrix theory

- Banks, Fischler, Shenker, & Susskind 1997: a candidate holographic theory of everything
- N x N matrices describe N “D0 branes” (particles)
- Trace of matrix = average position in that dimension
- Circumference of *M* dimension = Planck length



Macroscopic wave equation from Matrix theory

Matrix Hamiltonian stripped to macroscopic (kinematic) essentials

$$\hat{H} = \frac{R}{2\hbar} tr\hat{\Pi}^2$$

Becomes

$$\frac{\partial^2 u}{\partial x^2} + \frac{4\pi i}{\lambda} \frac{\partial u}{\partial z^+} = 0$$

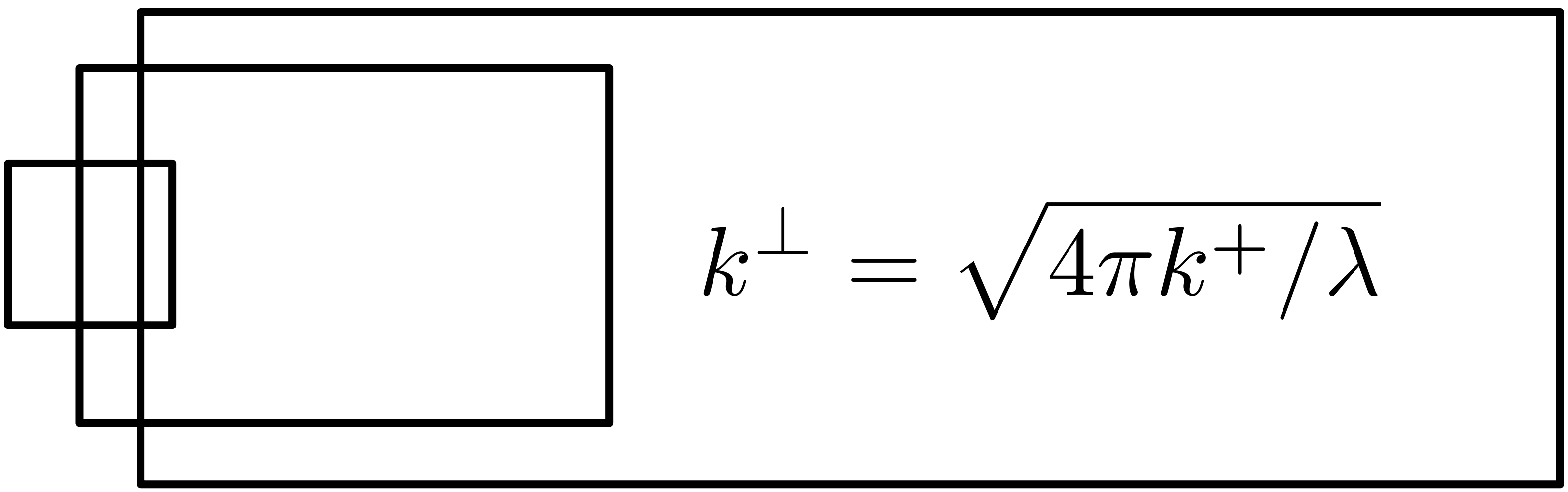
- Schrodinger equation, with z^+ = time and *u(x)* = wavefunction of matter position
- ="paraxial wave equation" with Planck wavelength carrier
- New quantum relationship between spacelike surfaces
- Quantum mechanics without Planck's constant
- "Bohr atom" for spacetime states?

CJH and M. Jackson:arXiv:0812.1285 PhysRevD.79.124009

Wave modes mix longitudinal and transverse dimensions

- Wavepacket spreading: slow transverse diffusion or diffraction
- Becomes more ray-like on large scales
- not the same as field theory limit
- New uncertainty principle:

$$\langle \Delta x^2 \rangle > \lambda \Delta L^+/2$$



$$k^\perp = \sqrt{4\pi k^+/\lambda}$$

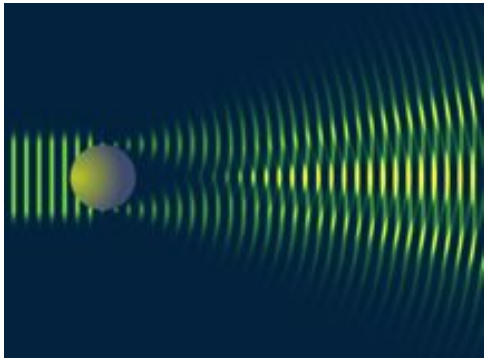
Approach to the classical limit

Angles become **less uncertain** (more ray-like) at larger separations:

$$\Delta\theta^2 > l_P / L$$

Transverse positions become **more uncertain** at larger separations:

$$\Delta x^2 > l_P L$$



- Not the classical limit of field theory
- Indeterminacy and nonlocality persist to macroscopic scales

Different limits of unification theory

Fundamental theory

Particle states, localized collisions: field theory

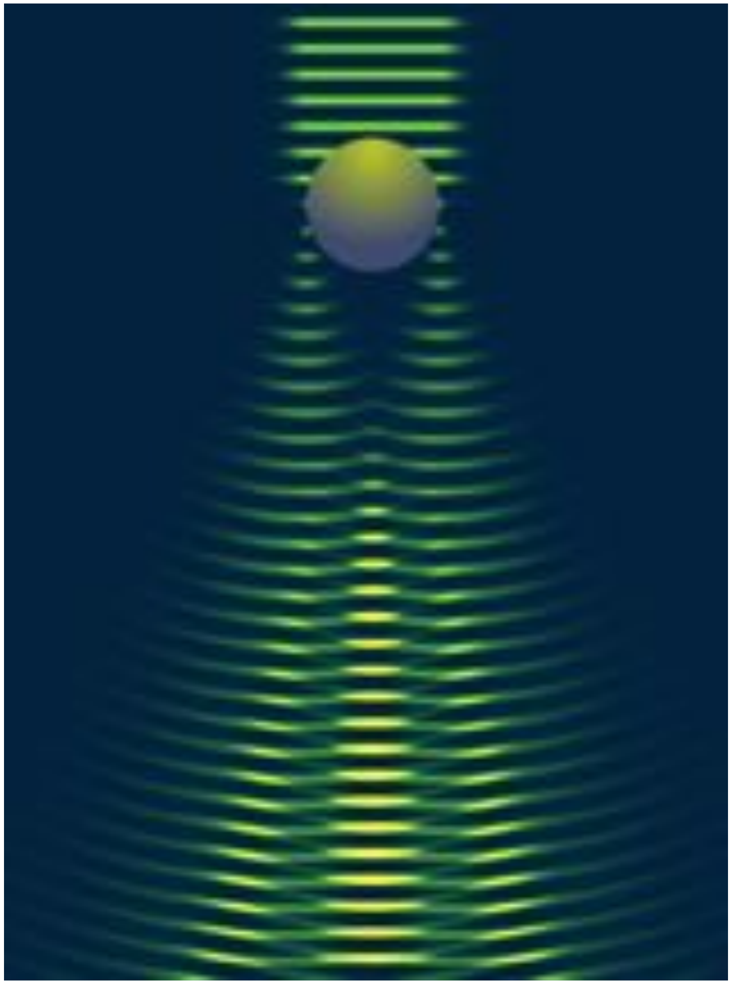
Nonlocal event positions: holographic wave modes

Wave Theory of Spacetime

Adapt wave optics to theory of "spacetime wavefunctions"

Transverse indeterminacy from interference of Planck waves

Allows calculation of observable correlation and holographic noise with no parameters



Survey of theoretical background: **arXiv:0905.4803**

Arguments for the new indeterminacy

- Wavepackets with maximum frequency, information bounds, black hole evaporation, matrix theory
- Non-commuting clock operators (arXiv:1002.4880)

Arguments for spatial coherence of jitter

- Locality, matrix theory

Ways to calculate the noise

- Wave optics solutions
- Planck wavelength interferometer limit
- Precise calibration from black hole entropy

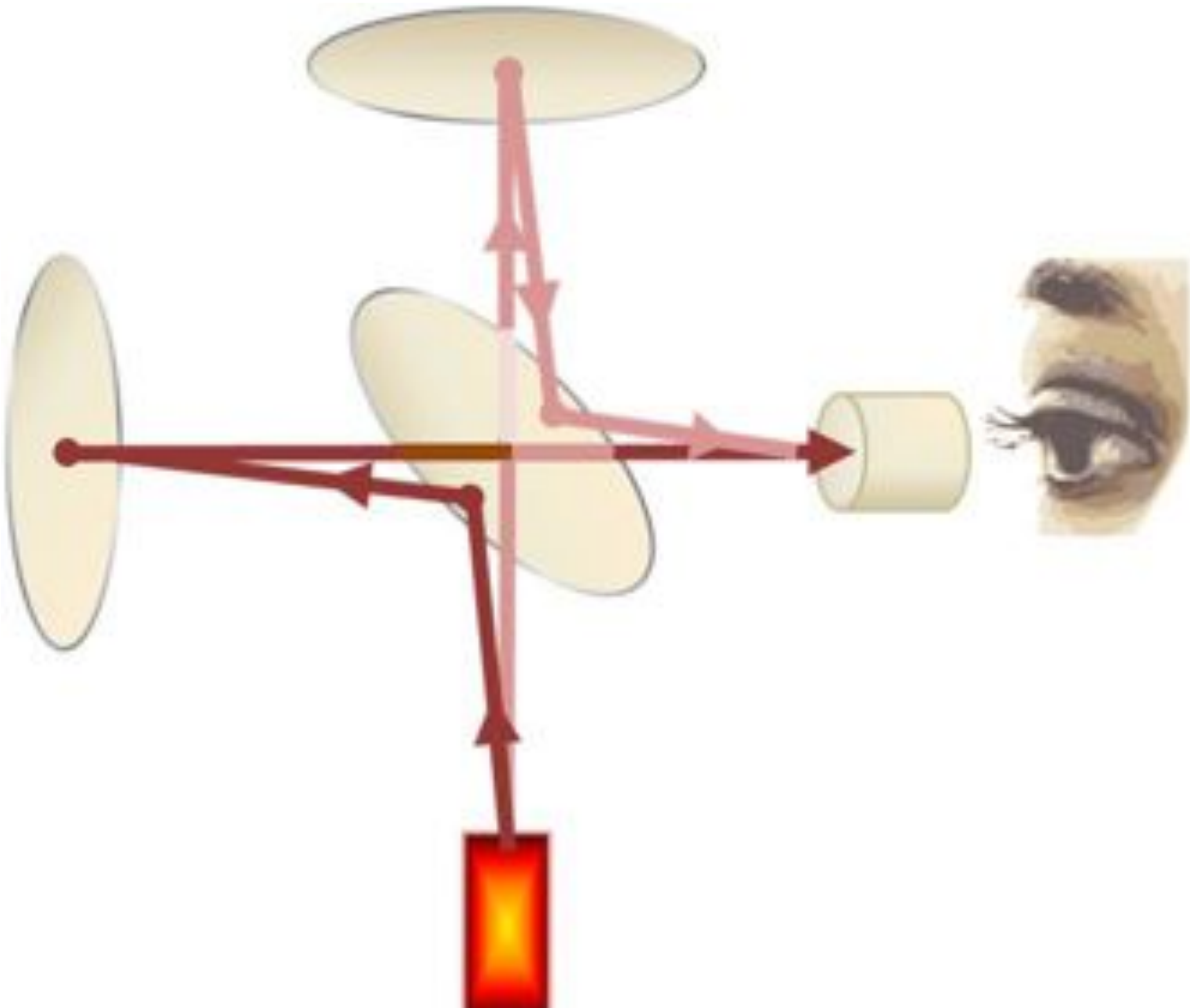
No argument is conclusive: motivates an experiment!

Michelson Interferometers

Devices long used for studying spacetime: interferometers

Albert Michelson

Michelson interferometer



Albert Michelson reading interference fringes

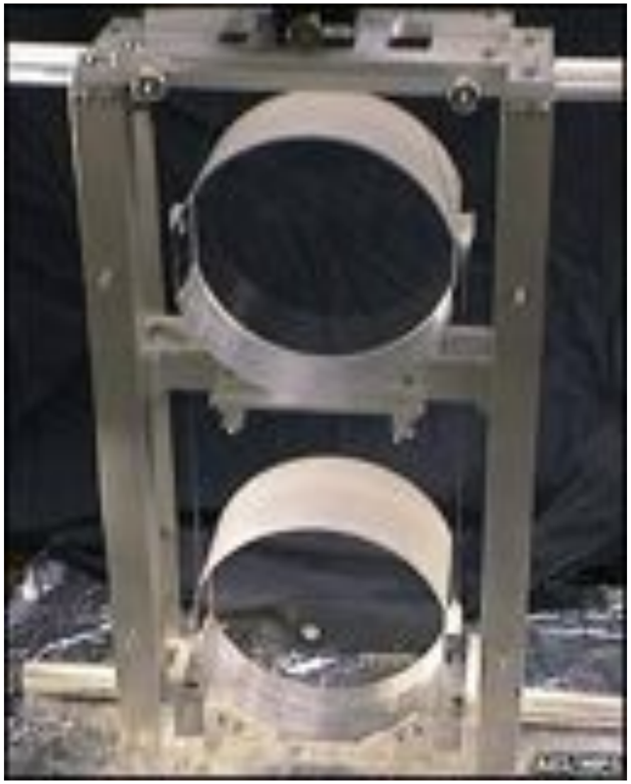
First and still finest probe of space and time

Original apparatus used by Michelson and Morley, 1887

Michelson and team in suburban Chicago, winter 1924, with partial-vacuum pipes of 1000 by 2000 foot interferometer, measuring the rotation of the earth

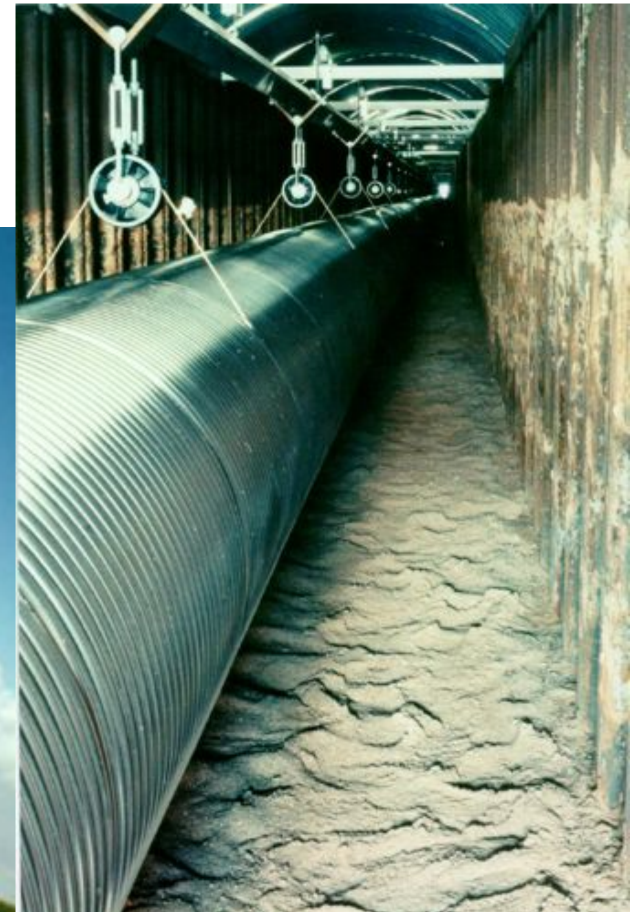
Attometer Interferometry

Interferometers now measure transverse positions of massive bodies to $\sim 10^{-18}\, m/\sqrt{Hz}$ *over separations ~10^3 m*



GEO600 beam tube and beamsplitter

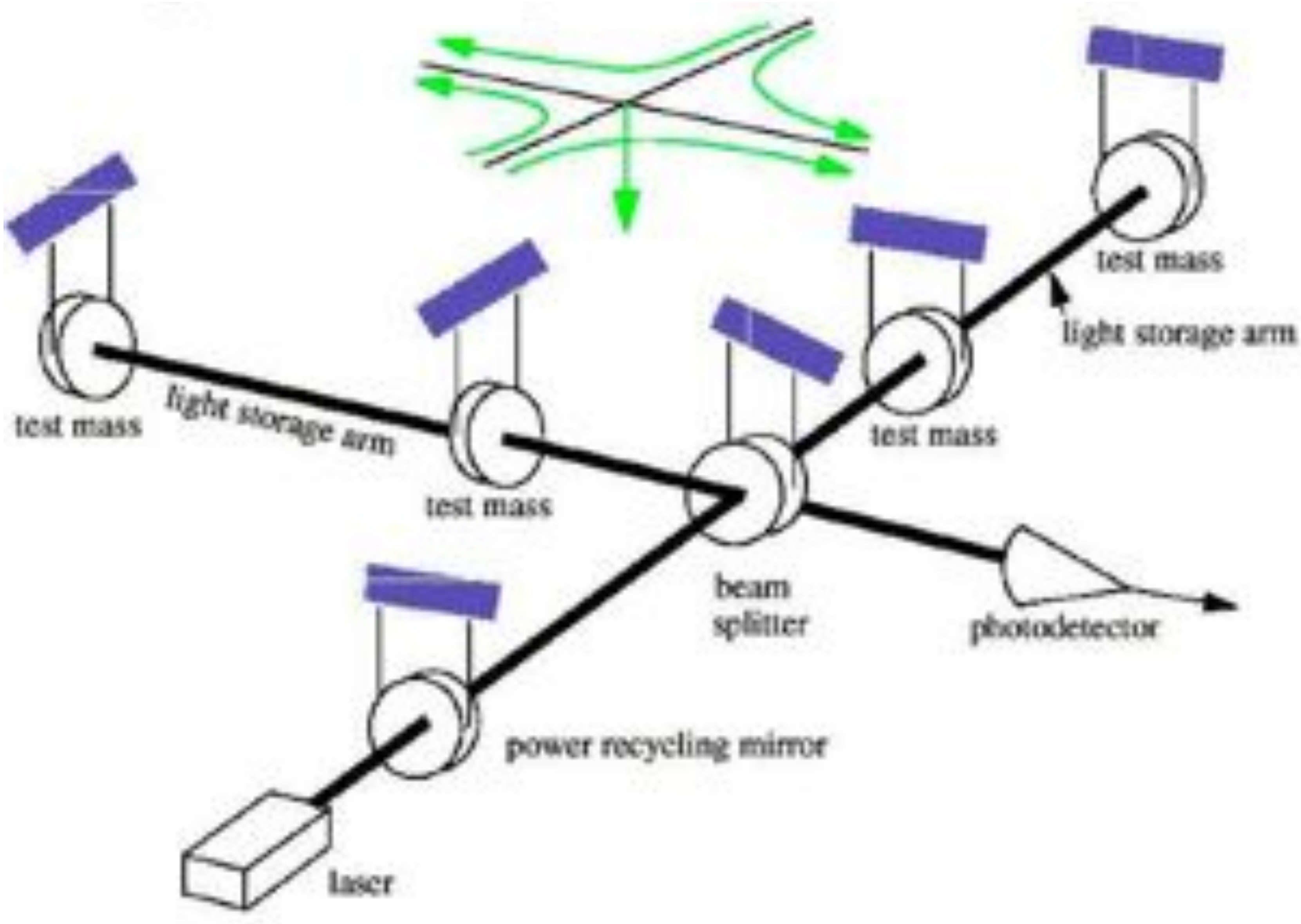
GEO-600 (Hannover)



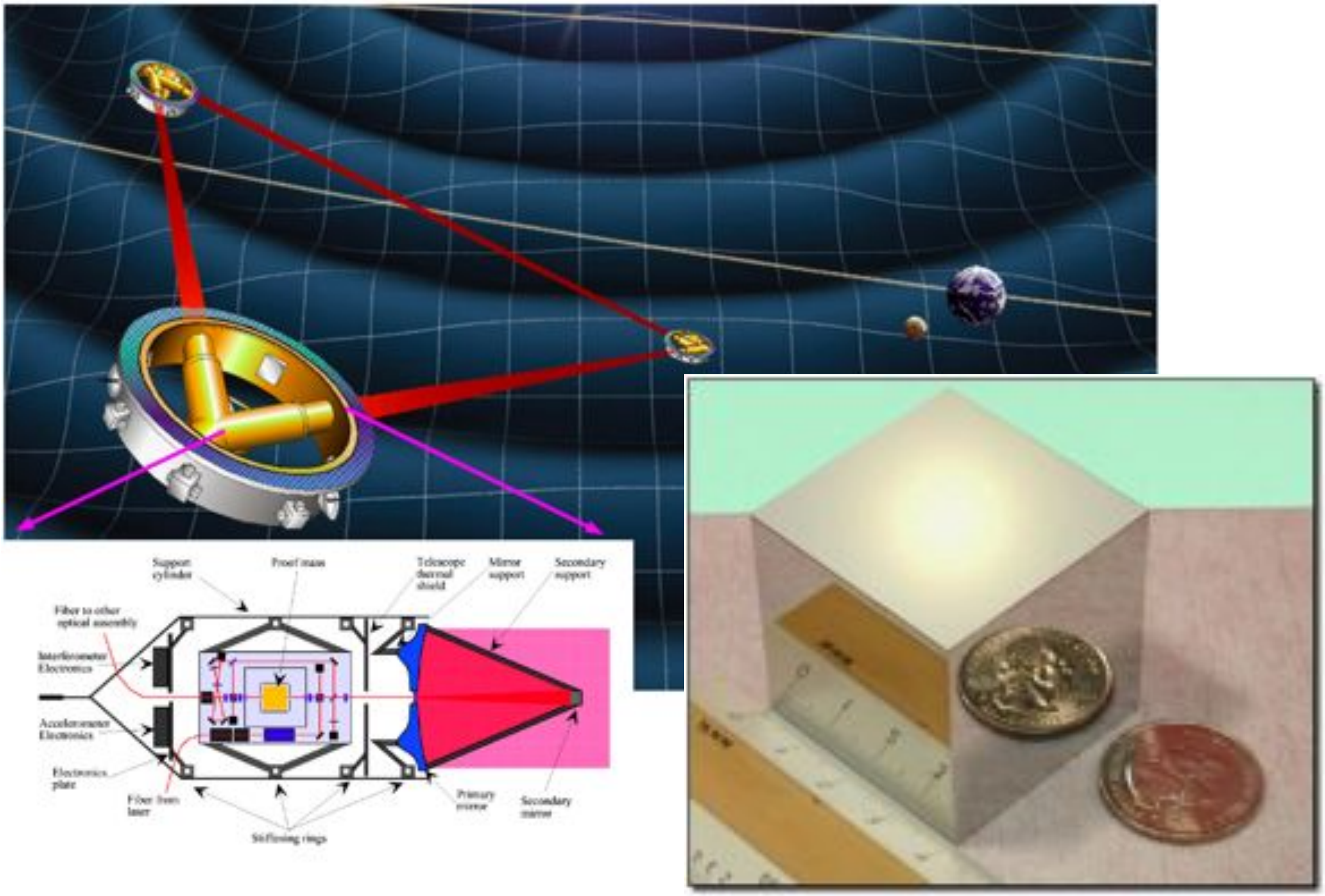
LIGO: Hanford, WA and Livingston, LA

Designed for gravitational waves at
audio frequencies (50 to 1000 Hz)

LIGO interferometer layout



Future LISA mission: 5 million kilometers, ~ 0.1 to 100 milliHertz



Holographic Noise in Interferometers

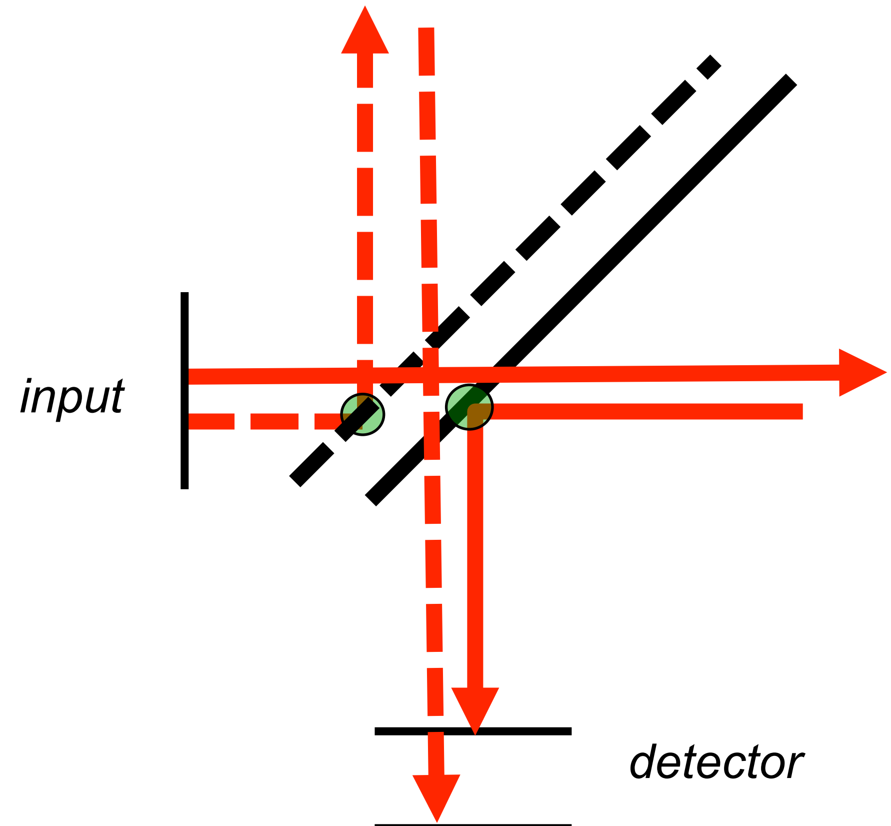
tiny position differences caused by spacetime wave blurring

holographic noise in signal: “Movement without Motion”

“Nature: the Ultimate Internet Service Provider”

Holographic noise in a Michelson interferometer

Jitter in beamsplitter position leads to fluctuations in measured phase



Range of jitter depends on arm length:

$$\Delta x^2 = \lambda_P L$$

this is a new effect predicted with no parameters

Interferometers as holographic clocks

Time is not an observable

Must be measured by physical clocks

Suppose clock operators live in 2D, associated with holographic null sheets

Clocks have an orientation

Time measurements in 3D in different directions do not commute at the Planck scale

Leads to the holographic noise in comparison of clocks in different directions (e.g., laser wavefronts in Michelson interferometers)

Over short time intervals, interferometers are much more stable than atomic clocks

CJH: arXiv:1002.4880

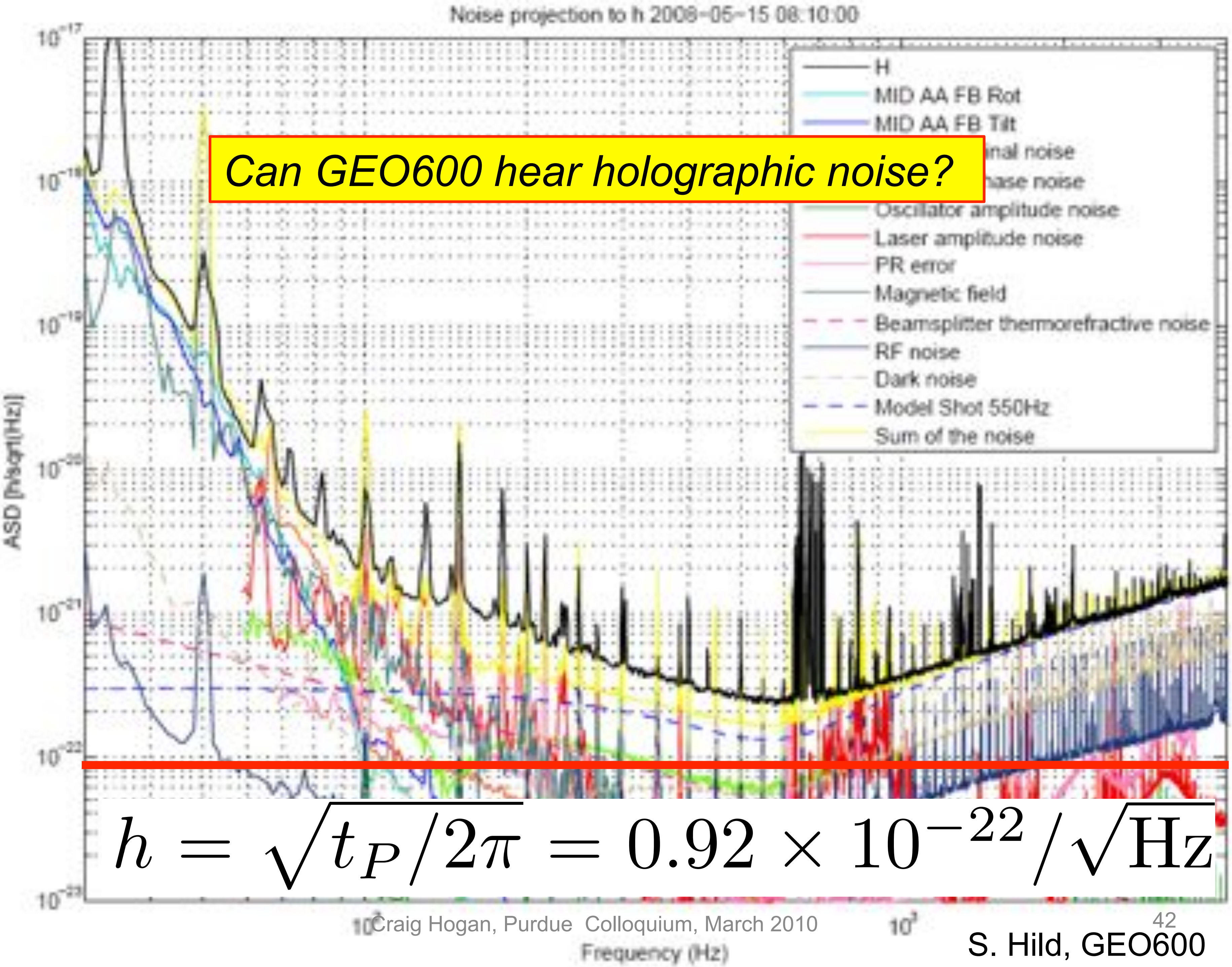
Universal Holographic Noise

Spectral density of equivalent strain noise independent of frequency:

$$h \approx \sqrt{t_P} = 2.3 \times 10^{-22} \mathrm{Hz}^{-1/2}$$

Detected noise spectrum can be calculated for a given apparatus

CJH: arXiv:0712.3419 Phys Rev D.77.104031 (2008)
CJH: arXiv:0806.0665 Phys Rev D.78.087501 (2008)
CJH & M. Jackson: arXiv:0812.1285 Phys Rev D.79.12400 (2009)
CJH: arXiv:0905.4803
CJH: arXiv:1002.4880



Can GEO600 hear holographic noise?

$$h = \sqrt{t_P/2\pi} = 0.92 \times 10^{-22}/\sqrt{\mathrm{Hz}}$$

S. Hild, GEO600

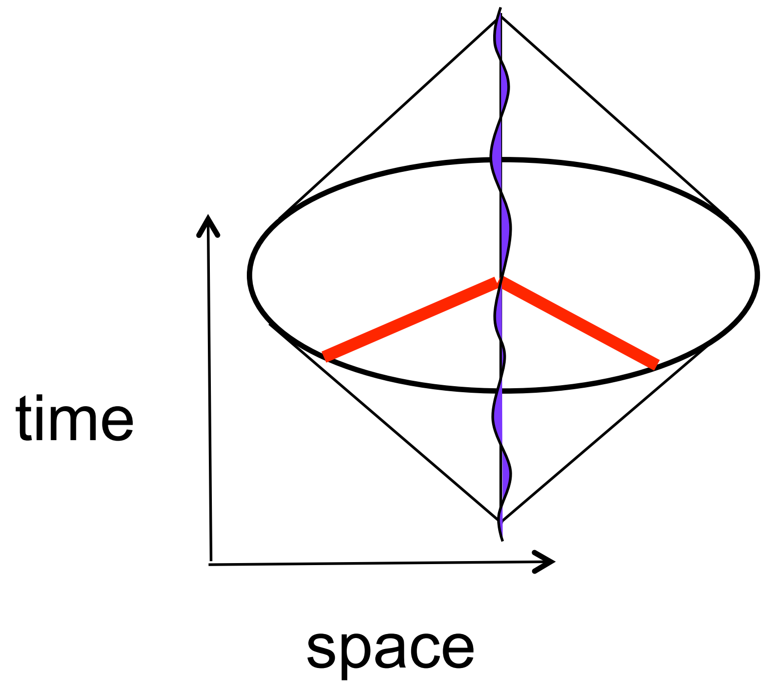
Current experiments: summary

- Interferometers are the best technology for detecting the effect
- Most sensitive device, GEO600, operating close to Planck sensitivity
- GEO600 “mystery noise”: ~2 years of checking
- A definitive sub-Planck limit or detection is difficult with GEO600: evidence is based on noise model
- LIGO: wrong configuration to study this effect
- No experiment has been designed to look for holographic noise
- More convincing evidence: new apparatus, designed to eliminate systematics of noise estimation

The Fermilab Holometer

We are developing a machine specifically to probe the minimum interval of time:

"Holographic Interferometer"



Spacetime diagram of an interferometer

(həʊˈlɒmɪtə(r)) [f. HOLO- + -METER, Cf. F. *holomètre* (1690 Furetière), ad. mod.L. *holometrum*, f. Gr. ὁλο- HOLO- + μέτρον measure.]

1696 PHILLIPS (ed. 5), *Holometer*, a Mathematical Instrument for the easie measuring of any thing whatever, invented by Abel Tull. **1727-41** CHAMBERS

Strategy for Our Experiment

Direct test for the holographic noise

Positive signal if it exists

Null configuration to distinguish from other noise

Sufficient sensitivity

Provide margin for prediction

Probe systematics of perturbing noise

Measure properties of the holographic noise

Frequency spectrum

Spatial correlation function

Correlated holographic noise in nearby interferometers

Matter on a given null wavefront “moves” together

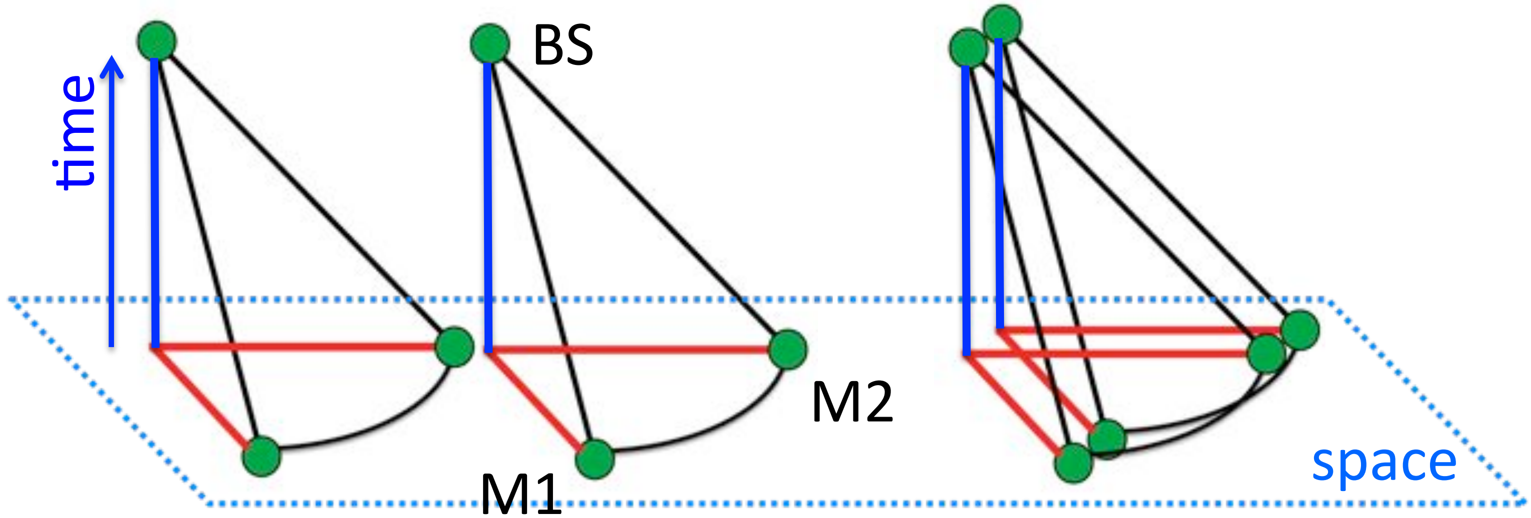
no locally observable jitter should depend on remote measurements

phase uncertainty accumulates over *~L*

Spacelike separations within causal diamond must collapse into the same state (i.e., clock differences must agree)

Nonoverlapping spacetime volumes, uncorrelated noise

overlapping spacetime volumes, correlated holographic noise



Experiment Concept

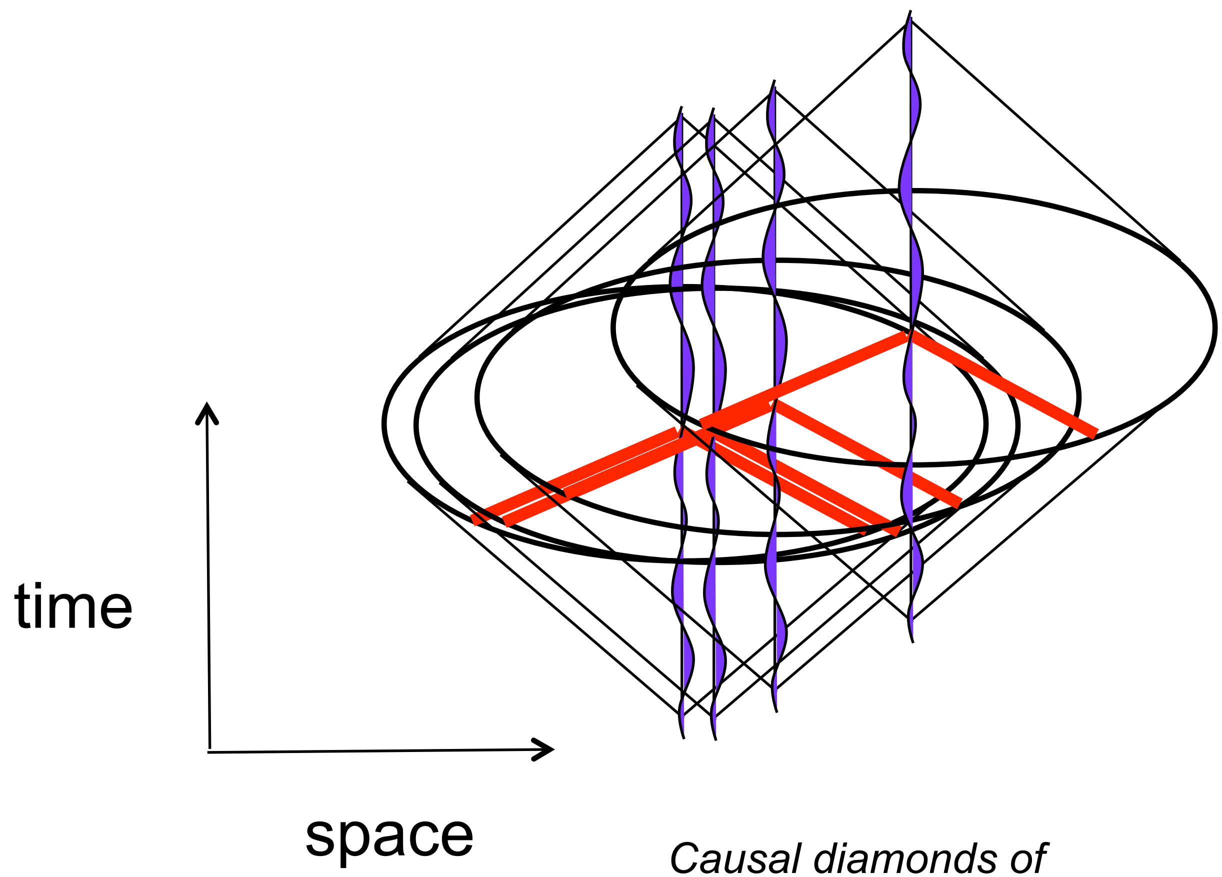
Measurement of the correlated optical phase fluctuations in a pair of isolated but collocated power recycled Michelson interferometers

exploit the spatial correlation of the holographic noise

use the broad band nature of the noise to measure at high frequencies (MHz) where other correlated noise is expected to be small

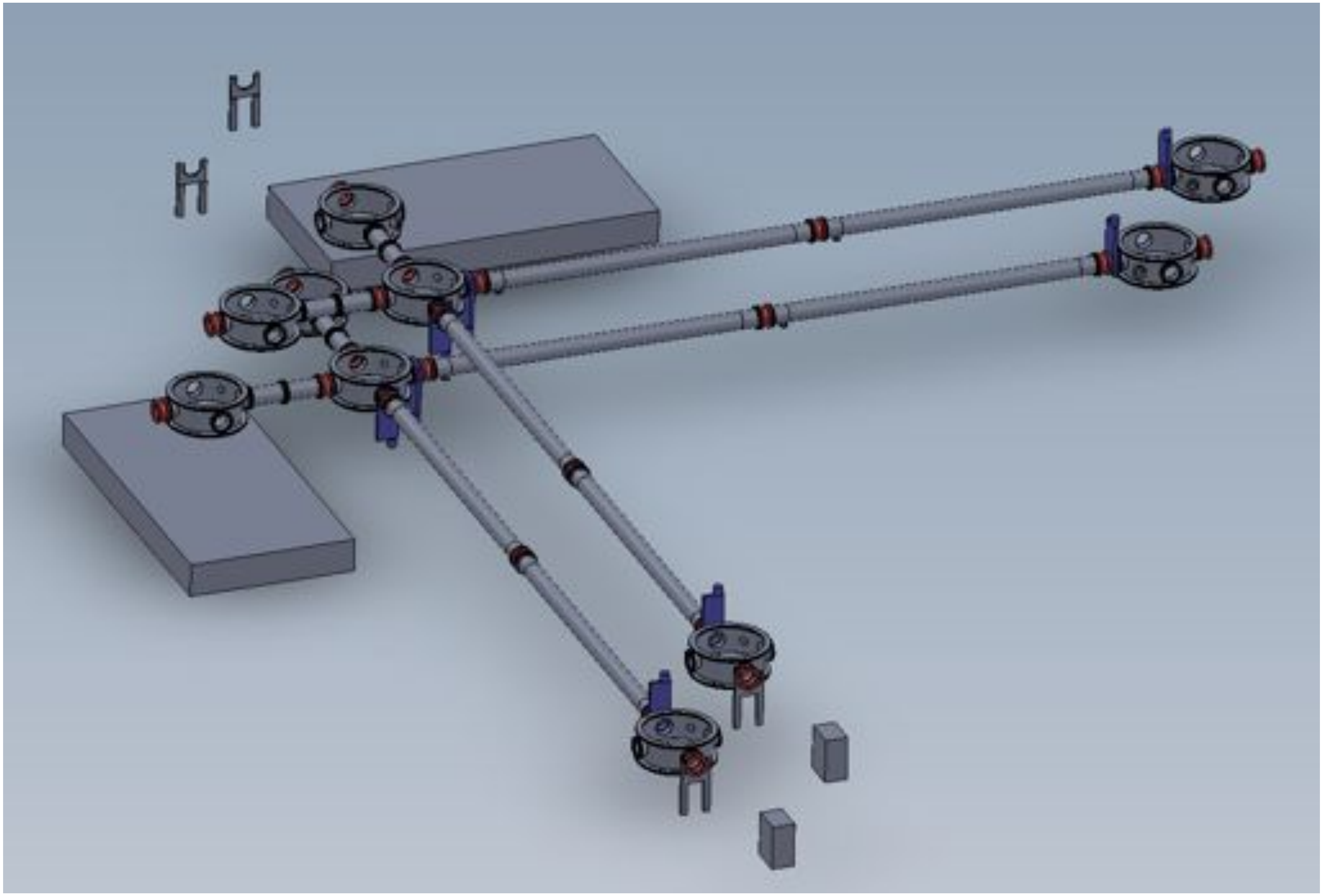
Fermilab holometer: a stereo search for holographic noise

Compare signals of two 40-meter Michelson interferometers at different separations and orientations



Causal diamonds of beamsplitter signals

Holometer layout (shown with 20 foot arms in “close” configuration)



Broadband system noise is uncorrelated

Coherently build up holographic signal by cross correlation

holographic signal = photon shot noise after

$$t_{\rm obs} > \left(\frac{h}{P_{\rm BS}}\right)^2 \left(\frac{\lambda_{\rm opt}}{\lambda_{\rm Pl}}\right)^2 \left(\frac{c^3}{32\pi^4 L^3}\right)$$

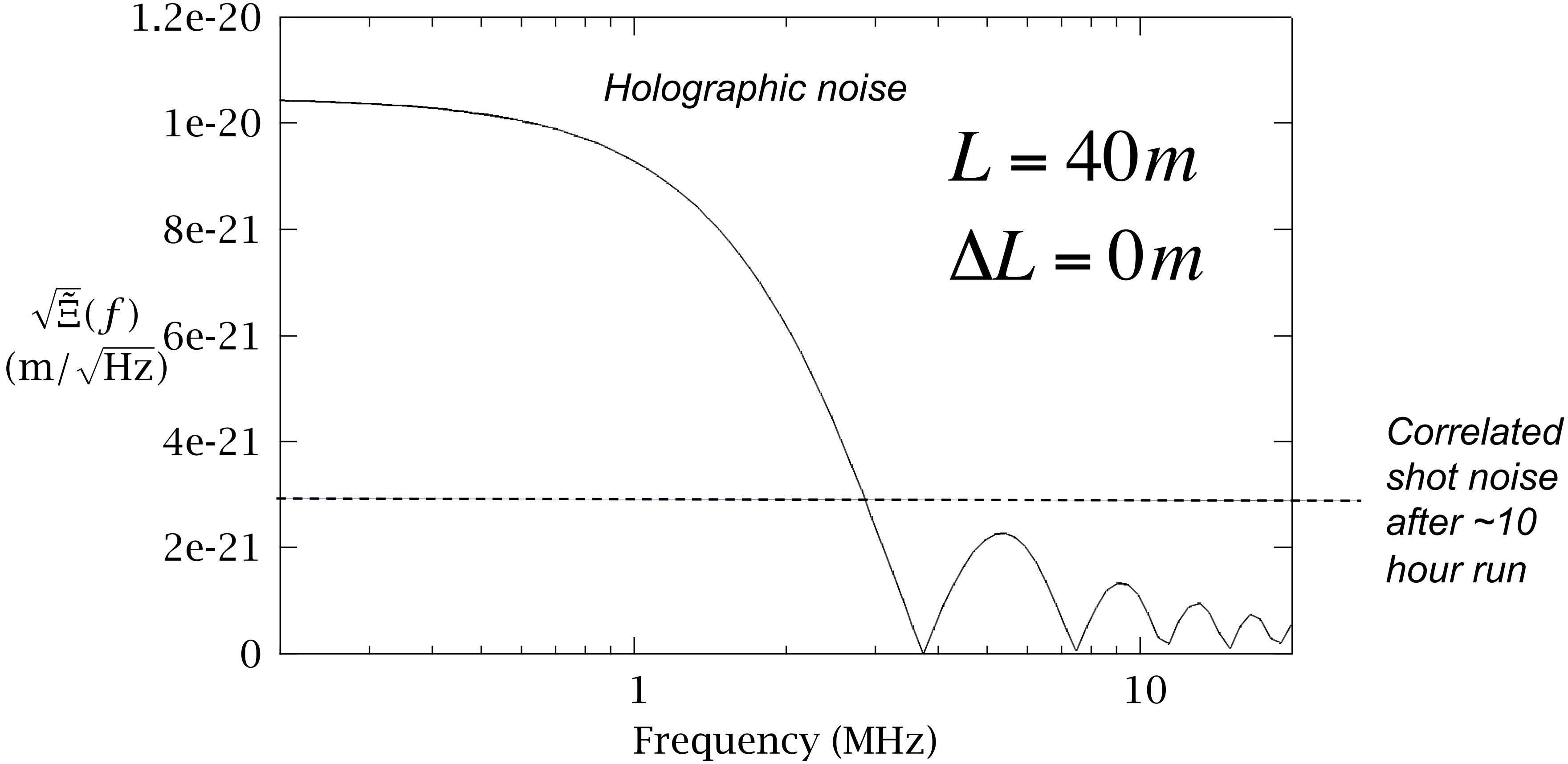
For beamsplitter power P_{BS}=2 kW, arm length L=40m, time for three sigma measurement is about an hour

Thermal lensing limit on beamsplitter power drives design

Reject spurious correlations in the frequency domain

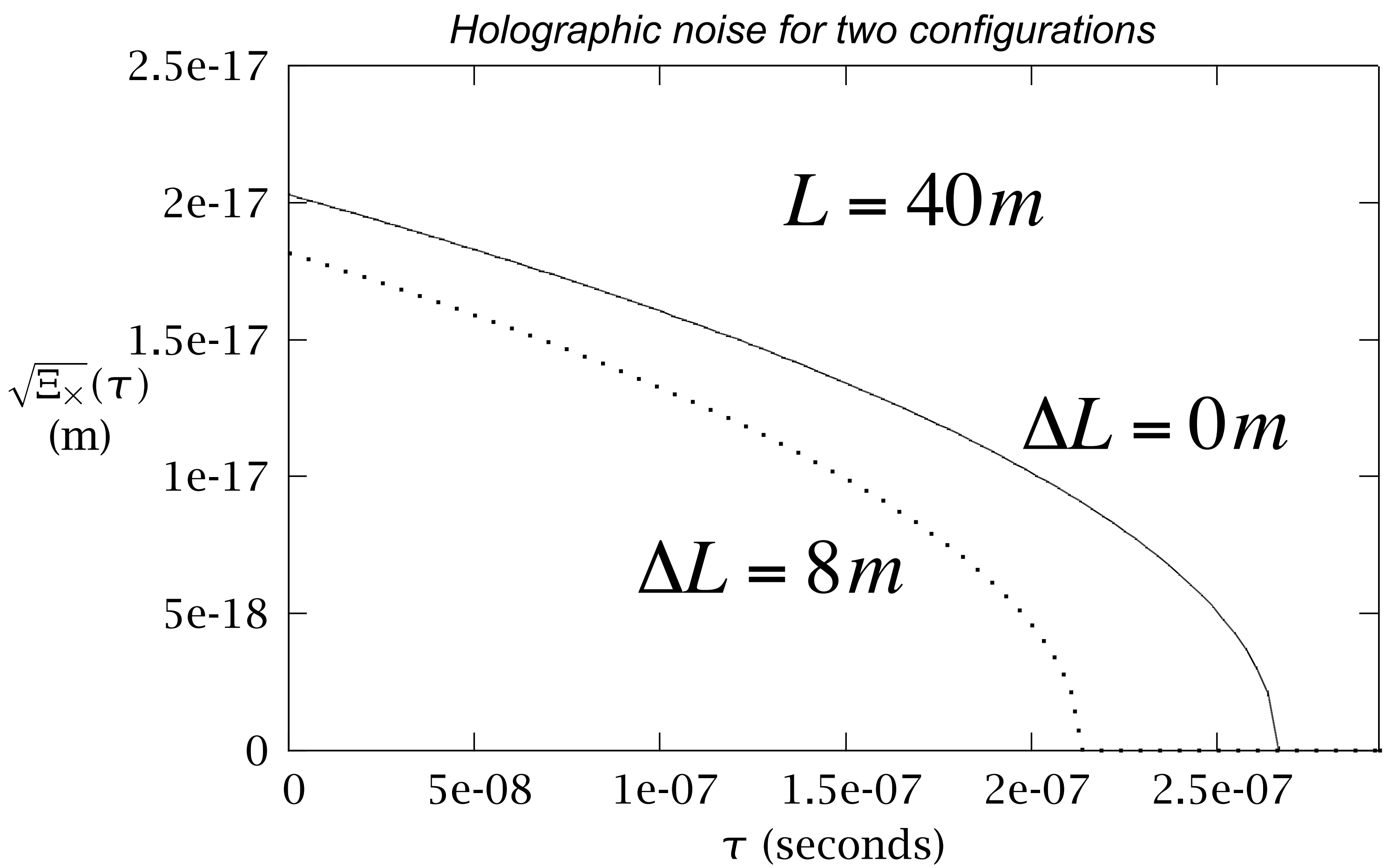
Predicted Planck-amplitude frequency spectrum

$$\tilde{\Xi}(f) = \frac{c^2 2 t_P}{\pi (2\pi f)^2}[1 - \cos(f/f_c)], \qquad f_c \equiv c/4\pi L$$

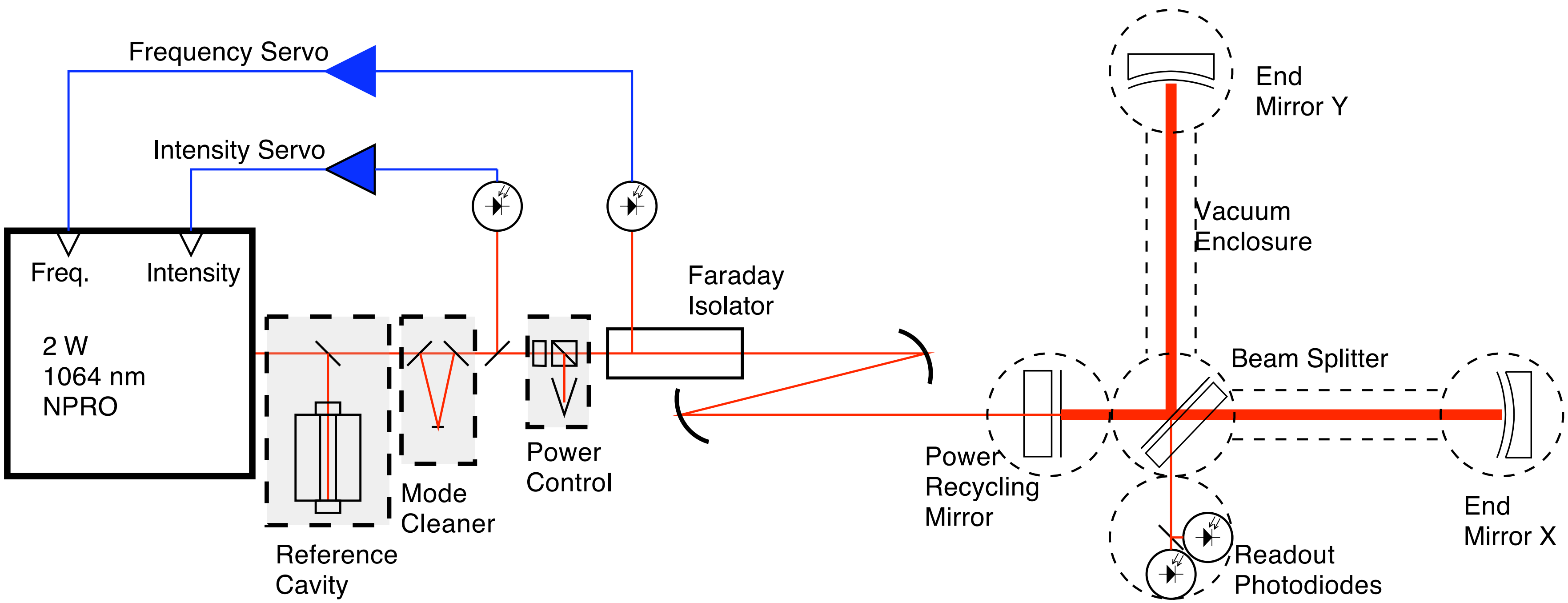


Predicted time-domain correlation, decorrelation

$$\begin{aligned} \Xi_\times(\tau) &\approx (\lambda_P/\pi)(2L - 2\Delta L - c\tau), \qquad 0 < c\tau < 2L - 2\Delta L \\ &= 0, \qquad c\tau > 2L - 2\Delta L. \end{aligned}$$

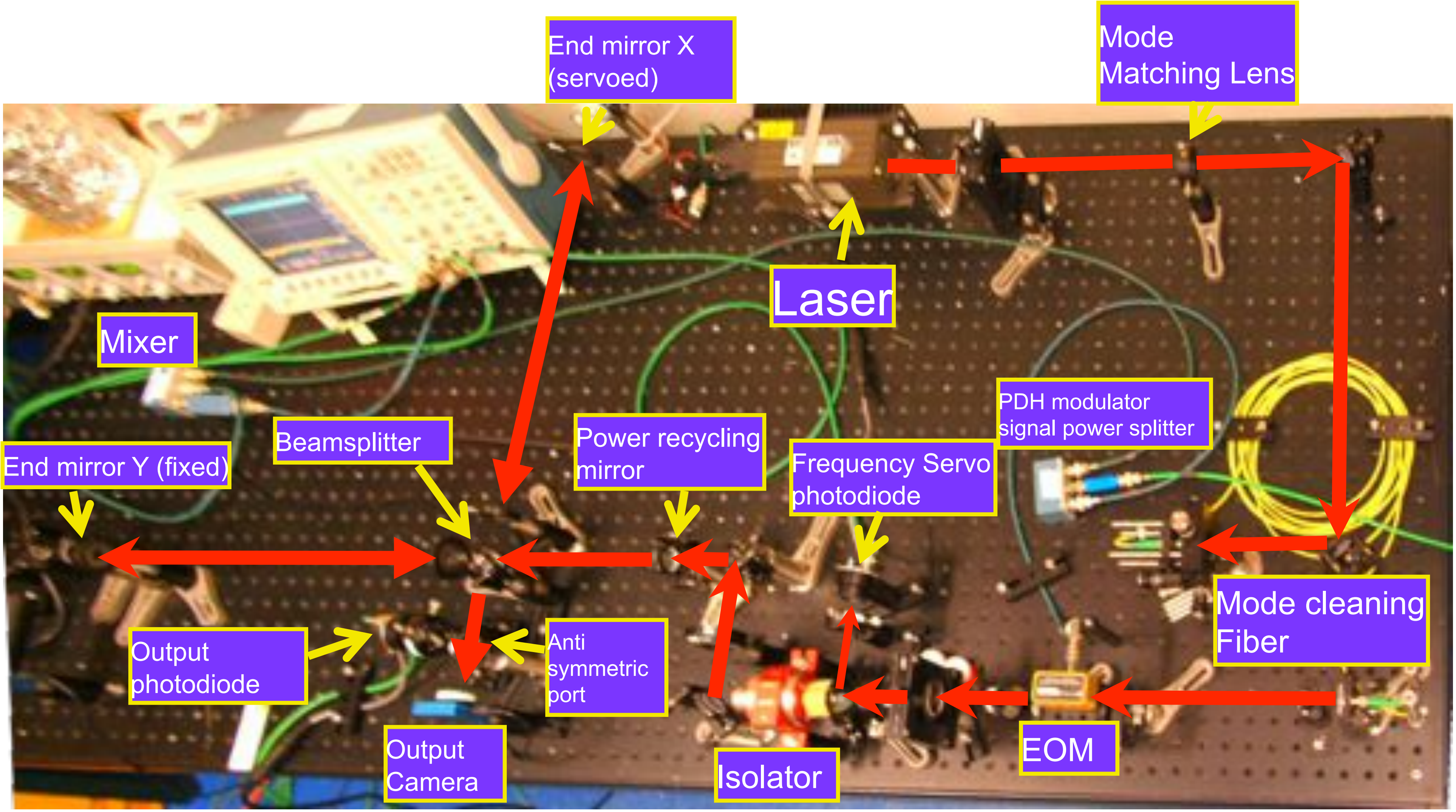


Optical layout: standard power-recycled Michelson



S. Waldman, MIT

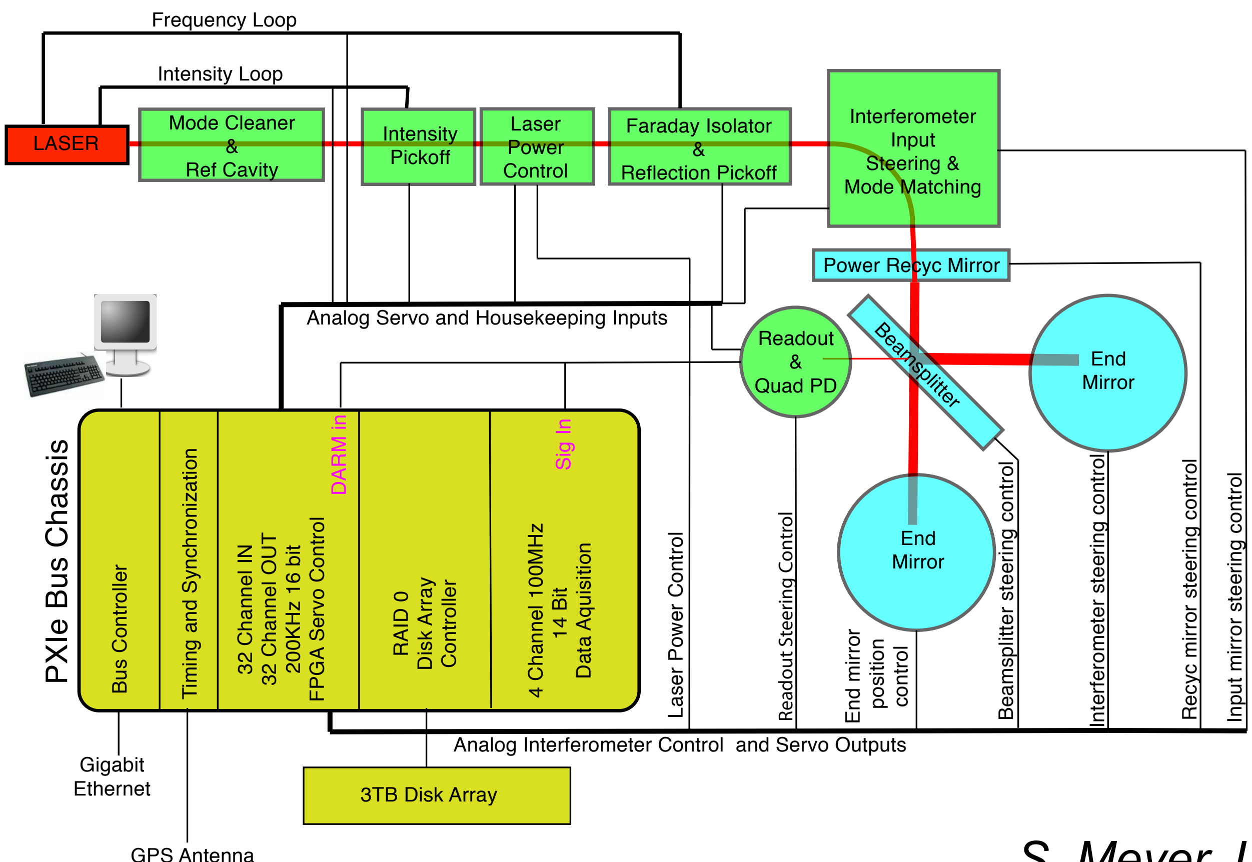
Table-top prototype power-recycled Michelson interferometer in the Fermilab Linac lab



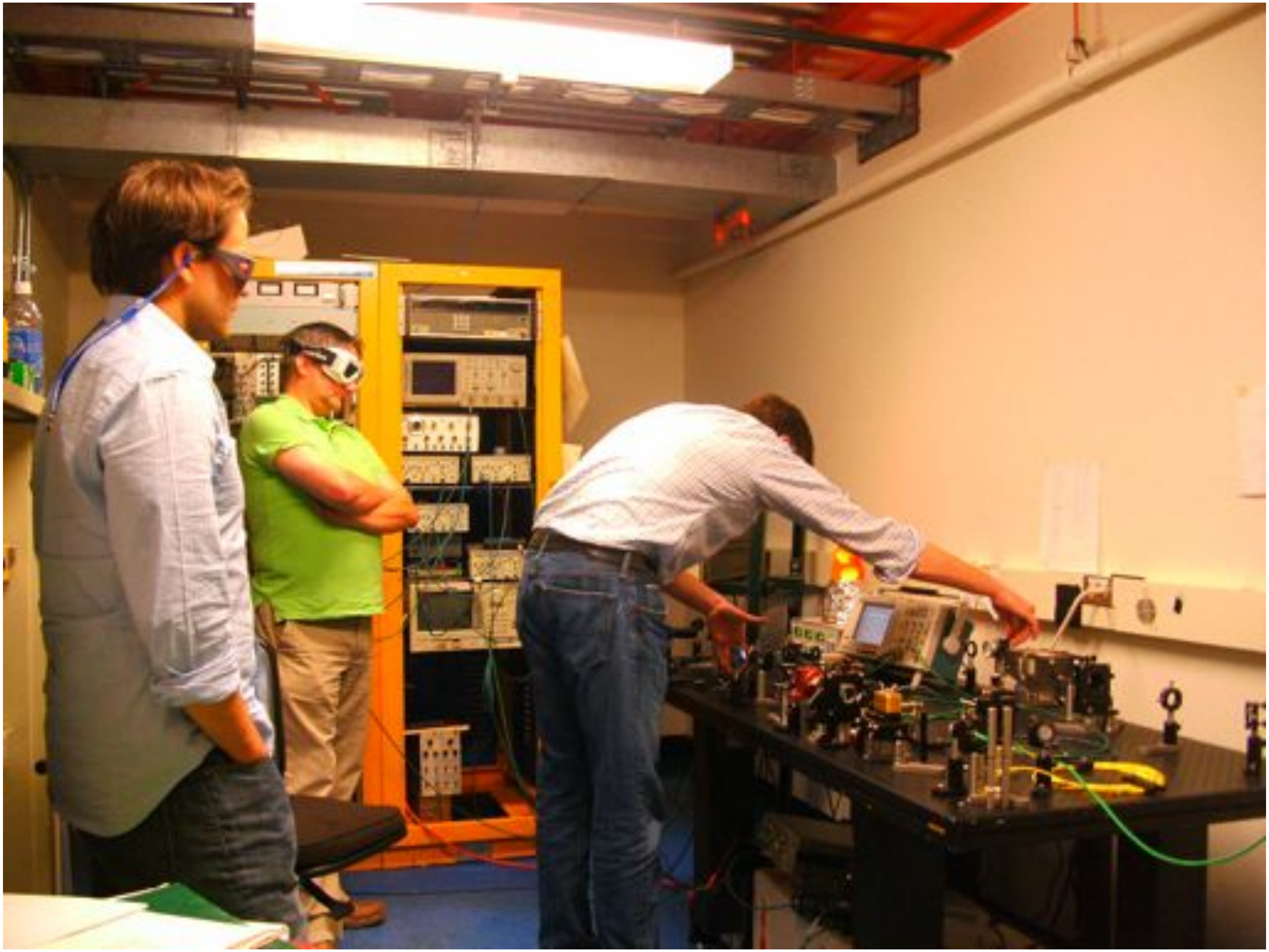
Control & data system

Off-the-shelf components and control software

Designed to control RF noise



S. Meyer, U. Chicago



Status of the Fermilab Holometer

- Team:
  - Fermilab (A. Chou, G. Gutierrez, CJH, E. Ramberg, J. Steffen, C. Stoughton, R. Tomlin, W. Wester)
  - MIT (R.Weiss, S.Waldman)
  - Caltech (S. Whitcomb)
  - University of Chicago (S. Meyer + students)
  - University of Michigan (R. Gustafson)
  - includes LIGO experts
- Building tabletop prototypes at Fermilab
  - Successful edge-locked interferometer, power recycled cavity
- Designing 40m system
- Developing & testing detectors, electronics, control systems

Physics Outcomes

If noise is not there,

Constrain interpretations of holography

But no direct challenge to widely cherished beliefs

If it is detected, experiments probe Planck scale unification

Study holographic relationships among matter, energy, space, time

Shape interpretation of fundamental theory

If we find holographic noise, so what?

Directly verify the “movement without motion” of spacetime

Directly measure the minimum interval of space and time

Show that reality is a kind of hologram

Data on unification of mass-energy and spacetime, directionality of time measurements

Absolute limit to bandwidth: technology implications